AD-A169 779 HUMAN THERMOREGULATORY MODEL FOR IMMERSION IN COLD WATER(U) ARMY RESEARCH INST OF ENVIRONMENTAL MEDICINE NATICK MA P TIKUISIS ET AL. JUN 86 USARIEM-M-39/86 1/1

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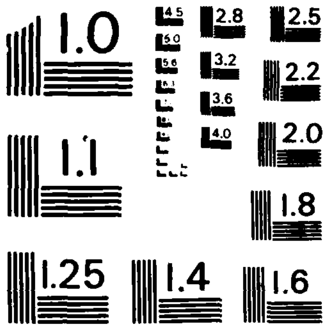
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER M39/86	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Human Thermoregulatory Model for Immersion in Cold Water		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Peter Tikuisis, Richard R. Gonzalez and Kent B. Pandolf		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Research Institute of Environmental Medicine Natick, MA 01760-5007		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 3E162777A878 WU 083
11. CONTROLLING OFFICE NAME AND ADDRESS Same as 9, above		12. REPORT DATE June 1986
		13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

thermoregulation, mathematical model, cold-water immersion, convective heat loss, thermal neutrality

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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HUMAN THERMOREGULATORY MODEL FOR IMMERSION IN COLD WATER

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A mathematical model of thermoregulation based on the concepts of Stolwijk and Hardy (Pflugers Arch 291, 129-162 (1966)) and Montgomery (Ann Biomed Eng 2, 19-46 (1974)) has been developed to simulate human physiological responses to cold-water immersion. Data were obtained from experiments where thirteen healthy male volunteers were totally immersed under resting and nude conditions for 1 h in water temperatures of 20 and 28°C. Mean measured rectal temperature (T_{re}) fell by about 0.9 and 0.5°C in 20 and 28°C water for all subjects, yet mean measured metabolic rate (M) rose by about 275 and 90 W for the lean mass group (n=7) and 195 and 45 W for the normal mass group (n=6). To predict the observed T_{re} and M values, the present model differed from its predecessors by a) determining a thermally neutral body temperature profile such that the measured and predicted initial values of T_{re} and M were matched, b) including thermal inputs for shivering from the skin independent of their inclusion with the central temperature to account for the observed initial rapid rise in M, c) confining the initial shivering to the trunk region to avoid an overly large predicted initial rate of rectal cooling, and d) calculating the steady state convective heat loss by assuming a zero rate of heat storage in the skin compartment.

Index Terms: thermoregulation, mathematical model, cold-water immersion, convective heat loss, thermal neutrality.

Since the inception of mathematical models of human thermoregulation (see review by Hardy (14)), data to test these models for cold-water immersion have been available yet have been scarcely applied. Mathematical models of thermoregulation can be steady-state or dynamic. Steady-state models apply where a heat balance exists, and therefore, are limited to the prediction of physiological responses that do not change with time. Most studies of cold-water immersion are, however, concerned with the transient responses upon immersion. Dynamic models can be applied to predict these responses.

Dynamic models can be empirically or rationally-derived. Empirical models use mathematical relationships derived from experimental data. A number of empirical models have been developed to predict thermal and metabolic responses to cold-water immersion (15,27). Although relatively simple to use, predictions from these models are limited to subject and environmental conditions that closely resemble the experimental conditions from which the models were derived.

Rationally-derived or theoretical models of thermoregulation use physical representations of the human body to simulate physiological responses to a change in the environment. Such models provide a useful theoretical device to evaluate and interpret experimental data, and potentially can be applied to a wide range of subject classifications and environmental conditions. The theoretical models assessed by Hardy (14) were found inadequate for predicting human responses to cold environments. Among these was the Stolwijk-Hardy model (24) originally developed to predict the physiological responses of nude man in an air environment. In 1974, Montgomery (20) adapted their model for cold-water immersion, yet confined its validation to the measurements of skin, ear, and rectal temperatures, but not to metabolic responses. In 1976, Gordon et al. (12) extended the concepts of Wissler (28) and Stolwijk and Hardy (24) to

model the physiological responses to a transient cold air exposure. However, Wissler (29) found this model unsuitable for predicting the response to cold-water immersion. Other models that Wissler evaluated included his own and Stolwijk-Hardy, yet, the agreement between measured and predicted values of temperature, metabolic rate, and net sensible heat loss was found to be less than satisfactory. Wissler did, however, suggest that those interested in applying the Stolwijk-Hardy model to simulate immersion in cold water should consult Montgomery's work (20).

In our study using data of resting and nude subjects totally immersed in cold water, we found the Montgomery model not wholly satisfactory for predicting transient changes in rectal temperature and metabolic rate, yet with certain modifications of the model, good agreement was obtained. This paper describes these modifications and presents a comparison between the measured and predicted thermoregulatory response for whole body immersion in cold water. Data from experiments of whole body immersion were used since, as will be seen, the heat losses to the water are limited to convective heat transfer which can easily be determined once a steady-state skin temperature is attained.

METHODS

Data presently used were available from a series of whole body water immersion studies (5,11). Thirteen healthy male volunteers were totally immersed under resting and nude conditions for 1 h in water temperatures of 20 and 28°C. Since a subject's thermal and metabolic response depends largely on his body composition (8,16,17,19,23,27), this study classified the subjects into two groups, those of lean composition and those of normal composition.

Mean ($\pm$ SD) anthropometric values of the lean subject group (n=7) were: height = 174.9 (4.5) cm, weight = 69.0 (7.5) kg, skinfold = 5.83 (0.75) mm, body fat = 9.67 (1.57)%, and surface area = 1.83 (0.11) m^2. Values for the normal

subject group (n=6) were: height = 175.7 (6.4) cm, weight = 79.2 (13.1) kg, skinfold = 11.82 (4.26) mm, body fat = 17.62 (4.11)%, and surface area = 1.94 (0.17) m^2.

MATHEMATICAL MODEL AND THEORETICAL CONSIDERATIONS

The model used in the present study is based largely on the Montgomery version (20) of the Stolwijk-Hardy model (24). The human body is treated as a passive heat transfer system and is divided into six distinct segments, the head modelled as a sphere and the trunk, arms, hands, legs, and feet modelled as cylinders. The model is shown schematically in Fig. 1. Heat flows radially in the model segments and heat transfer between segments is through conduction via the central blood. Each segment is composed of four concentric annular compartments, the core, muscle, fat, and skin, as proposed by Stolwijk and Hardy (24). In addition, the central blood is a single compartment located within the trunk segment. The Montgomery version of expanding the number of core and muscle compartments by four each is not used. Instead, the relative weight distribution, thermal-capacitance values, basal metabolic rates, and basal blood-flow rates of all compartments proposed by Montgomery is used.

The thermoregulatory controlling system integrates the thermoreceptor output signals of certain compartments and determines the response through efferent commands. For example, cold signals may induce shivering. The thermoreceptor output signal of each compartment is determined by the difference between the compartment's current temperature and its set-point value. Set-point values are established before immersion and remain constant throughout the immersion. The efferent commands involve sweating, vasomotor response, and shivering. Unless otherwise indicated, the thermoreceptor and efferent output simulations follow the method of Montgomery (20).

Thermal conductances between compartments were determined according to the method outlined by Stolwijk and Hardy (24). Thermal resistances for spherical and cylindrical geometries were obtained from Sekins and Emery (22). Thermal conductivity values for the core and muscle compartments were taken from Stolwijk (25), and those for the fat and skin compartments were taken from Sekins and Emery (22).

Since the subjects were totally immersed in water, both radiative and evaporative heat transfer from the body were considered negligible. Total respiratory heat loss was determined by the combined respired evaporative and respired convective heat losses of the trunk core (10) and by the basal respiratory heat loss of head core (25). The subjects breathed through a snorkel and therefore the respiratory heat loss was determined by assuming that the air breathed was fully saturated and at a temperature equal to the water temperature.

Initial and Set-Point Temperatures

Initial conditions assume thermal neutrality. By simulating an exposure to an arbitrary environment in the zone of thermal neutrality, the original Stolwijk-Hardy model (25) will generate equilibrium temperatures for each compartment including the central blood. The resultant initial temperatures are thus assigned as the set-point temperatures for thermoregulation. One drawback with this method is that the model's temperature profile, which is based on the standard man, does not necessarily match the subject's profile in his pre-immersion state, and therefore, thermoregulation may be arbitrarily imposed. Furthermore, any initial offset between measured and predicted temperatures will affect the level of agreement during the subsequent immersion phase.

Ideally, the initial temperature profile of the model should match the subject's. At present, it is not possible to measure the subject's temperature

profile, so certain assumptions must be made. First, in accordance with Stolwijk (25), it was assumed that the subject was thermally neutral in his pre-immersion state (this is reasonable considering that subjects were resting in a thermally neutral air environment before immersion). Second, it was assumed that the subject's measured pre-immersion metabolic rate represented his basal value (BMR) and that the model's trunk core temperature represented his rectal temperature (T_{re}).

A thermal neutral temperature profile can thus be determined for any subject by setting the rate of heat storage of each model compartment equal to zero and solving the resulting linear heat balance equations. Since the model contains a total of 25 compartments (6 segments x 4 compartments plus central blood, see Fig. 1), and therefore an equal number of heat balance equations, a trial and error procedure was adopted to simplify the solution of the compartment neutral temperatures. By pre-selecting a value of the central blood temperature, the system of equations reduced to six independent sets of four linear equations which could be readily solved using the Gauss Elimination method.

The subject was assumed to be in an air environment with 50% relative humidity and various trial combinations of air temperature and central blood temperature were selected until the solution yielded a) a trunk core temperature equal to the subject's measured pre-immersion rectal value, and b) a central blood temperature with no change in heat storage. The predicted neutral temperature profile obtained using this method for the normal subject group is shown in Fig. 2. The values shown are in good agreement with the values given by Stolwijk (25) and Stolwijk and Hardy (26). This procedure of determining the model's neutral temperature profile was applied with every set of mean group subject data.

Convective Heat Loss

A major theoretical obstacle for any thermoregulatory model is the determination of convective heat loss, especially in water immersion where heat transfer is many times greater than in air (4,23). Theoretically-determined values are subject to assumptions of body shape and water motion. Heat transfer is also sensitive to the skin-water temperature difference, and unless the heat transfer coefficient is precise, an unstable oscillation of skin temperature values may result in the model prediction once the skin temperature approaches the temperature of the water.

It has been shown experimentally that the mean weighted skin temperature ($\bar{T}_{sk}$) of nude subjects falls exponentially during immersion in cold water (27), and that the asymptotic limit is a temperature slightly higher than the water temperature, although the skin-water temperature difference increases with lowered water temperature (19,21,27). These experimental observations can be coupled with the theoretical determination of the convective heat transfer coefficient to arrive at a reasonable model prediction of convective heat loss.

During the transient phase of decreasing skin temperature, T_{sk} of each body segment was determined step-wise according to

$$T_{sk} = T_{sk_o} + (T_{sk_o} - T_{sk_{ss}}) \exp\left[S_{sk} \cdot \Delta t / C_{sk}(T_{sk_o} - T_{sk_{ss}})\right), \qquad (1)$$

where T_{sk_o} is the skin temperature at the beginning of the time step, $T_{sk_{ss}}$ is its steady-state value, S_{sk} is the rate of heat storage of the skin, Δt is the time step, and C_{sk} is the heat capacity of the skin. In this study, $T_{sk_{ss}}$ was assigned the experimentally measured value, yet an arbitrary value close to the temperature of the water could have been assigned without incurring a large error in determining the convective heat loss during the transient phase (see DISCUSSION). The rate of heat storage of the skin was determined through the thermal balance equation of the skin compartment:

$$S_{sk} = M_{sk} - C - K_{skbl} + K_{fsk}, \tag{2}$$

where M_{sk} is the metabolic rate of the skin, C is the convective heat transfer rate from skin to water, K_{skbl} is the conductive heat transfer rate from the skin to the blood, and K_{fsk} is the conductive heat transfer rate from the fat to the skin. The convective heat transfer rate was determined through fluid dynamic considerations (see Eq. 6 and APPENDIX). This calculation was carried out by assuming a water velocity of 0.005 m/s which represents the motion produced in "still" water by respiration and mild shivering (30). Although shivering intensity can be expected to increase with increased immersion time, a steady-state skin temperature was attained well before the water motion was seriously underestimated.

Equation 1 achieves two purposes: first, it retains the correct rate of change of skin temperature (i.e. $\dot{T}_{sk} = S_{sk}/C_{sk}$) when the exponent has a small value which is satisfied by the model constraint of limiting the change in temperature of any compartment to no more than 0.1°C per time step, and second, the exponential fall in skin temperature is accounted for.

Once the skin temperature was close to its assigned steady-state value (assumed by the model when the difference between T_{sk} and $T_{sk_{ss}}$ was less than 0.005°C), no further change in skin temperature occurred and the heat transfer from skin to water was determined through the thermal balance of the skin compartment with zero rate of heat storage, that is using Eq. 2 with $S_{sk} = 0$.

Efferent Shivering Command

Central to any thermoregulatory model for cold exposure is the efferent command for shivering. Montgomery (20) retained the Stolwijk (25) control equation for the shivering command which essentially is the product of a control coefficient, a central thermoceptor output signal and the appropriate skin (peripheral) thermoceptor output signal. As will be seen, such an expression is

incapable of predicting the initial rapid rise in metabolic rate that has been repeatedly observed for cold-water immersion (1,9,15). In fact, there is sufficient evidence to support the view that to some extent, shivering is independently controlled by skin thermoreceptors (1,3,6,8,13,27). The initial rapid increase in metabolic rate appears to correlate well with the initial rapid decrease in skin temperature. Therefore, the controller equation for shivering in the present model is hypothesized as:

$$\mathrm{CHILL} = A_D * (\mathrm{C1} \cdot \mathrm{COLD(1)} \cdot \mathrm{COLDS} + \mathrm{C2} \cdot (\mathrm{COLDS/PBF})^{\mathrm{C3}}), \tag{3}$$

where CHILL is the metabolic response (W) to the cold stress, A_D is the subject's surface area, COLD(1) is the head core thermoreceptor output (equal to the difference between the current temperature of the head core and its set-point value only when the head core temperature is less than its set-point value, otherwise the output value is zero), COLDS is the weighted skin thermoreceptor output, PBF is the subject's percent body fat, and C1 through C3 are fitting constants. In the Montgomery version (20), only the second term is present, and the coefficient representing $A_D \cdot$C1 was assigned the value of 24.4 W (21 kcal/h).

Shivering is the body's defense mechanism to counter hypothermia. However, an increase in shivering intensity entails to an extent a corresponding increase in muscular blood flow. If the muscle temperature is lower than that of the central blood, then any increase in blood flow to that muscle will lower the central blood temperature. In fact, given that the metabolic rate initially rises rapidly, the corresponding increased blood flow predicted for the arm and leg segments will indirectly cause a fall in trunk core temperature (through conductive heat exchange with the central blood) much more rapidly than observed. To avoid this, the present model initially confined shivering to the trunk muscle (since its temperature was close to that of the central blood) and introduced shivering of the arm and leg muscles exponentially. The exponential

time constant was attenuated by the subject's percent body fat according to:

$$\begin{aligned} \text{CHILM (trunk muscle)} &= 0.85 + 0.12 \exp (C4 \cdot t/PBF) \\ \text{CHILM (arm muscle)} &= 0.05\ (1 - \exp (C4 \cdot t/PBF)) \\ \text{CHILM (leg muscle)} &= 0.07\ (1 - \exp (C4 \cdot t/PBF)) \end{aligned} \qquad (4)$$

where CHILM is the weighing factor of the corresponding muscle's contribution to the overall shivering, C4 is a fitting constant, t is the elapsed time since immersion, and the values 0.85, 0.05 and 0.07 were taken from Stolwijk and Hardy (26). Note that if t is sufficiently long, the CHILM factors revert to the values given by Stolwijk and Hardy (26) which were also used by Montgomery (20).

Simulation Procedure

The anthropometric characteristics of the model subject assumed the average values for the group it was simulating. The neutral (and set-point) temperature profile was determined separately for each subject group and exposure based on the group's mean measured pre-immersion rectal temperature and metabolic rate. This metabolic rate was assigned as the model subject's basal metabolic rate. Values of air temperature ($T_{air-neutral}$) and blood (T_{bl}) temperature were selected so that thermal neutrality was achieved in the pre-immersion state as outlined earlier (see Table 1). The model subject was then exposed to a simulation of whole body immersion in the cold water.

RESULTS

Figures 3 to 6 illustrate the measured ($\pm$SE) and predicted values of the rectal (modelled as the trunk core) temperature and metabolic rate. To obtain these predicted values, the constants C1 through C4 (see Eqs 3 and 4) were assigned the values listed in Table 1. Also shown in these figures are the predicted values using the present model but without the independent shivering command from the skin and without the exponential onset of shivering of the arm and leg muscles.

The predicted temperature profile for the normal subject group after 1 h of immersion in 20°C water is illustrated in Fig. 2. Every compartment except the trunk muscle shows a decrease in temperature; the increase in temperature in the trunk muscle is slight, from 37.10 to 37.33°C. Decreases in temperature in the other compartments range from small changes in the core and muscle of active compartments to large changes in the inactive compartments and the fat and skin compartments of all segments. Figure 2 is representative of the model prediction (in a qualitative sense) of the lean subject group and for immersion in 28°C water of both groups.

Figure 7 shows the model prediction of mean body temperature, trunk core temperature, mean skin temperature, metabolic rate, and convective heat loss for the normal subject group immersed in 20°C water. The mean body temperature ($\bar{T}_b$) was determined by weighting each compartment's temperature according to its heat capacity (25). The mean skin temperature ($\bar{T}_{sk}$) was similarily determined from all skin compartments. The overall convective heat loss was determined by summing the convective heat loss of each segment.

DISCUSSION

Efferent Shivering Command

To obtain agreement with the measured metabolic and thermal response to cold-water immersion, an efferent shivering command based, in part, independently on the skin temperature, and an exponential onset of the arm and leg shivering were required. The possibility of an independent skin temperature effect on shivering was not excluded in the Stolwijk-Hardy and Montgomery models (although it was not used), and as pointed out by Cabanac (6), the debate over additive versus multiplicative combinations of thermoreceptor output signals has yet to be resolved. In the present model, the initial shivering command from the skin appears to be dependent on the skin thermoreceptor

output signal raised to the power 1.5. Furthermore, this signal is attenuated by the subject's percent body fat, also raised to the same power. Without this independent efferent command from the skin, it was not possible to predict the observed initial rapid rise in metabolic rate. This is demonstrated by the dashed lines in Figs. 3 through 6 where the coefficient C1 was adjusted to correspond to the value used by Montgomery (20) and the coefficient C2 was set to zero.

One reason that the rapid initial rise in metabolic rate cannot be predicted with the shivering command based on the product COLD(1) · COLDS (see Eq. 3) alone is that the head core temperature is very slow to change initially (1,3), and therefore, despite the rapid initial change in skin temperature, the product of cold signals from the head core and skin has a depressed value in the initial stage of immersion. In fact, the central temperature may initially increase (9) in which case the product has a zero value.

An alternate shivering command could have been based on the time derivative of the skin temperature (29). Such a command would produce a transient increase in shivering intensity. However, our data suggests that if transients are present (variability in subject response makes this difficult to discern), they persist for much longer than the few minutes it takes for a steady-state skin temperature to be reached.

The exponential onset of the arm and leg shivering was necessary to avoid a model prediction of a large initial decrease in trunk core temperature. Such a decrease would stem from increased blood flow from the cooler muscles of the arms and legs thereby lowering the central blood temperature which in turn would lower the trunk core temperature (26). The exponential factor governing the onset of arm and leg shivering (see Eq. 4) was modelled according to the subject's percent body fat such that the shivering activity of a lean subject began sooner than that of the normal subject. Although, experimental evidence to

support this dependence on body composition is lacking, this feature is a necessary, yet rationally-derived, modelling construct to predict the measured thermal response.

Set-Point Temperatures

The method of obtaining a thermal neutral temperature in this study is unique. Essentially the thermal neutral temperature profile and thus the set-point values for thermoregulation were determined according to the pre-immersion data of the subject and not on the expected values for the standard man as used in the Stolwijk model (25). The inherent possibility of adjustable set-point temperatures, which our method assumes, has been reported previously (13). The advantage that our method provides over the Stolwijk method is to assure that the model subject is thermally neutral at the outset of an exposure and that the measured and predicted initial values of rectal temperature and metabolic rate are matched.

The thermal neutral skin temperatures (see Fig. 2) may appear high and, in fact, are higher than the measured pre-immersion values. However, the theoretical values represent the whole skin compartment and not just the surface which was measured. During immersion, the error is small in assuming that the steady-state temperature of the skin compartment equals the measured skin temperature (see below).

Tissue Conductance and Heat Transfer Coefficient

An important test and useful application of the present model is its prediction of average tissue conductance, k, and the convective heat transfer coefficient, h_c. These values can be calculated from the model predictions as (4):

$$k = C/(T_{re} - \hat{T}_{sk}), \quad (5)$$

and

$$h_c = C/(\hat{T}_{sk} - T_w), \quad (6)$$

where T_{re} is represented by the trunk core temperature and T_W is the water temperature. Table 2 lists these values for both subject classifications and exposures after 1 h of immersion. Steady-state conditions can be assumed at this time (2), as demonstrated in Fig. 7. The values of average tissue conductance shown in Table 2 are in good agreement with other reported values (4,9,19,23). In fact, the predicted increase of average tissue conductance with lowering water temperature is consistent with the decreasing insulative value of increasingly active muscle (17). Such a decrease was noted by both Craig and Drovak (9) and McArdle et al. (19) where T_W was lowered from 28 to 24°C. Further support of the model stems from its prediction of higher average tissue conductance for the lean subject group compared to the normal group.

The model-predicted values of the convective heat transfer coefficient (see Table 2) are in agreement with the values reported by Witherspoon et al. (30), Nadel et al. (21), and Strong et al. (27), but are significantly higher than those reported by Boutelier et al. (2). Such a disparity has already been noted by Boutelier et al. (2) and reasons given stem from differences in the measurement and theoretical determination of convective heat loss. It should be noted that the heat transfer coefficient is highly sensitive to the skin-water temperature difference. For instance, complete model agreement can be obtained for the h_C values between the 20 and 28°C exposures by increasing the steady-state skin temperature by less than 0.1°C for the exposure to 28°C water.

The procedure by which the present model determines the convective heat loss to the water avoids this sensitivity once steady-state of the skin temperature is achieved. Recall that the choice of the steady-state skin temperature was experimentally-determined; however, this choice could have been made arbitrarily without significantly affecting the final result since the convective heat loss is ultimately determined by the conductive heat flow from

the fat to the skin. This heat flow is only slightly affected by small changes in the steady-state value of the skin temperature. For example, if $T_{sk_{ss}}$ was raised from 21.0 to 21.5°C for the normal subject group immersed in 20°C water, the predicted convective heat loss to the water would change from 166.0 to 160.2 W/m^2. Note, however, that changing the skin temperature from 21.0 to 21.5°C would decrease the convective heat transfer coefficient (See Eq. 6) by 67% which demonstrates the potential disparity among reported values as pointed out by Boutelier et al. (2).

Mean Body Temperature

The present model can provide insight into the thermal response of the whole body from its prediction of the rate of change of mean body temperature. Since the mean body temperature for cold-water immersion can be approximated by (18)

$$\bar{T}_b = 0.33\ \bar{T}_{sk} + 0.67\ T_{re}, \tag{7}$$

the rate of change of mean body temperature should be less than the rate of change of rectal temperature after the skin temperature has reached its steady-state value. If one assumes that the rectal temperature can be represented by the trunk core temperature, then this prediction holds true, as can be seen from the estimated (slope of temperature against time) values of $\dot{\bar{T}}_b$ and $\dot{T}_{re}$ listed in Table 2.

To check on the internal consistency of the model, the rate of change of mean body temperature can alternatively be determined through the thermal balance equation for a resting body totally immersed in water by (20)

$$\dot{\bar{T}}_b = (M\text{-}C\text{-}H_R)/C_b \tag{8}$$

where H_R is the rate of total respiratory heat loss (from head and trunk core compartments) and C_b is the heat capacity of the whole body. The values determined in this fashion, shown in Table 2, are in agreement with those

estimated from the slope of temperature change with time. We conclude that the model is self-consistent with the prediction of thermal response to cold-water immersion.

Conclusion

A concern with models of the type presented here is the number of constants required to make the model's predictive capability valid yet relatively simple for general application. In the present case, three new constants were added when compared to the Montgomery model for cold-water immersion (20). However, these constants, C2 through C4, retained one value for both lean and normal subject groups and for both water immersion temperatures. Only the value of C1, which is the coefficient of the product of cold signals from the head core and skin for the efferent shivering command, changed value from 5 to 2 W/m^2 for the normal subject group immersed in 28°C water. Considering the complexity of human thermoregulation, the added number of constants to reach agreement with the observation is not onerous. Some adjustment of the present set of model constant values (see Table 1) may be necessary considering the high variability in subject response to cold stress (16,27), however, the present model construction which introduces a) an alternate method of determining a thermally neutral temperature profile, b) the addition of an independent shivering command from the skin, and c) the exponential onset of shivering of the arm and leg muscles may be generally applicable. Further testing is required to ascertain the model's predictive capability for exercised and clothed subjects.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Tammy J. Doherty for valuable discussions during the course of this work, Lee A. Stroschein for data acquisition and computer assistance, and Karen A. Nitchman and Dorothy Leader for technical assistance preparing the manuscript.

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Table 1: Measured* and model values for thermal neutrality in air and for response to cold water immersion

T_w (°C)	20		28	
Group Classification	lean	normal	lean	normal
BMR (W/m^2)*	49.4	47.2	50.5	42.5
T_{re} (°C)*	37.48	37.48	37.32	37.52
$T_{air\text{-}neutral}$ (°C)	28.60	28.85	28.25	29.80
T_{bl} (°C)	37.26	37.25	37.10	37.32
$T_{sk_{ss}}$ (°C)*	21.0	21.0	28.4	28.4
C1 (W/m^2)	5	5	5	2
C2 (W/m^2)	65	65	65	65
C3	1.5	1.5	1.5	1.5
C4 (min^{-1})	0.5	0.5	0.5	0.5

Table 2. Model prediction after 1 h of water immersion

T_w (°C)	20		28	
Group Classification	lean	normal	lean	normal
M (W/m^2)	221.1	154.0	94.8	64.4
C (W/m^2)	214.9	166.0	99.7	82.3
H_R (W/m^2)	17.6	12.9	6.4	5.1
T_{re} (°C)	36.54	36.61	36.93	37.00
k ($W/m^2/°C$)	13.83	10.63	11.69	9.57
h_c ($W/m^2/°C$)	214.9	166.0	249.3	205.8
$\dot{T}_{re}$* (°C/h)	-0.87	-1.13	-0.36	-0.64
$\dot{\bar{T}}_b$* (°C/h)	-0.36	-0.72	-0.32	-0.62
$\dot{\bar{T}}_b$**(°C/h)	-0.32	-0.67	-0.32	-0.62

*slope of temperature against time

**calculated using Eq. 8.

APPENDIX: Convective Heat Transfer Coefficient

The convective heat transfer coefficient for flow across spherical and cylindrical segments is determined by (20)

$$h_c = Kw\ Nu/d \tag{A1}$$

where Kw is the thermal conductivity of water, Nu is the Nusselt number, and d is the segment diameter. Convective heat transfer involves both forced and free convection.

The Nusselt number for forced convection is determined by (7)

$$Nu_{fo} = 0.66\ Re^{1/2}\ Pr^{1/3}, \tag{A2}$$

where Re is the Reynolds number and Pr is the Prandtl number. The Reynolds number is determined by

$$Re = V_w\ d/\ \nu, \tag{A3}$$

where V_w is the water velocity and ν is the kinematic viscosity of water. The Prandtl number is determined by

$$Pr = \nu/D, \tag{A4}$$

where D is the molecular diffusivity of water.

The Nusselt number for free convection is determined by (7)

$$Nu_{fr} = 0.54\ (Pr \cdot Gr)^{1/4}, \tag{A5}$$

where Gr is the Grashof number determined by

$$Gr = \beta g D^3\ (T_{sk} - T_w)/\nu^2, \tag{A6}$$

and where β is the coefficient of thermal expansion of water and g is the acceleration due to gravity.

If the ratio $G_r/R_e{}^2$ is small, then forced convection dominates, otherwise free convection dominates (7). When the ratio is near unity, it is assumed that the two terms are additive.

Figure Captions

Fig. 1. Schematic (not drawn to scale) of the human body (only one side shown) used in the thermoregulatory model. Each body segment is composed of four concentric annular compartments, the head modelled as a sphere and the others as cylinders. Length of the cylinders are given in cm (25). The central blood compartment is located within the trunk segment. The numbers in parenthesis represents the outer radii (cm) of the model segments for the normal subject group used in this study.

Fig. 2. Predicted temperature profiles for the normal subject group in the neutral air environment prior to immersion (open bar) and after 1 h of unclothed whole body immersion at rest (dashed bar). Compartments for each segment are ordered core, muscle, fat, and skin from left to right. The measured mean pre-immersion metabolic rate of 47.2 W/m^2 was inputed as the model subject's basal metabolic rate. To obtain thermal neutrality in an air environment with 50% relative humidity and an initial trunk core temperature equal to the mean pre-immersion rectal temperature of 37.48°C , an air temperature of 28.85°C and a blood temperature of 37.25°C were assigned. The final skin temperature was experimentally-determined (see text).

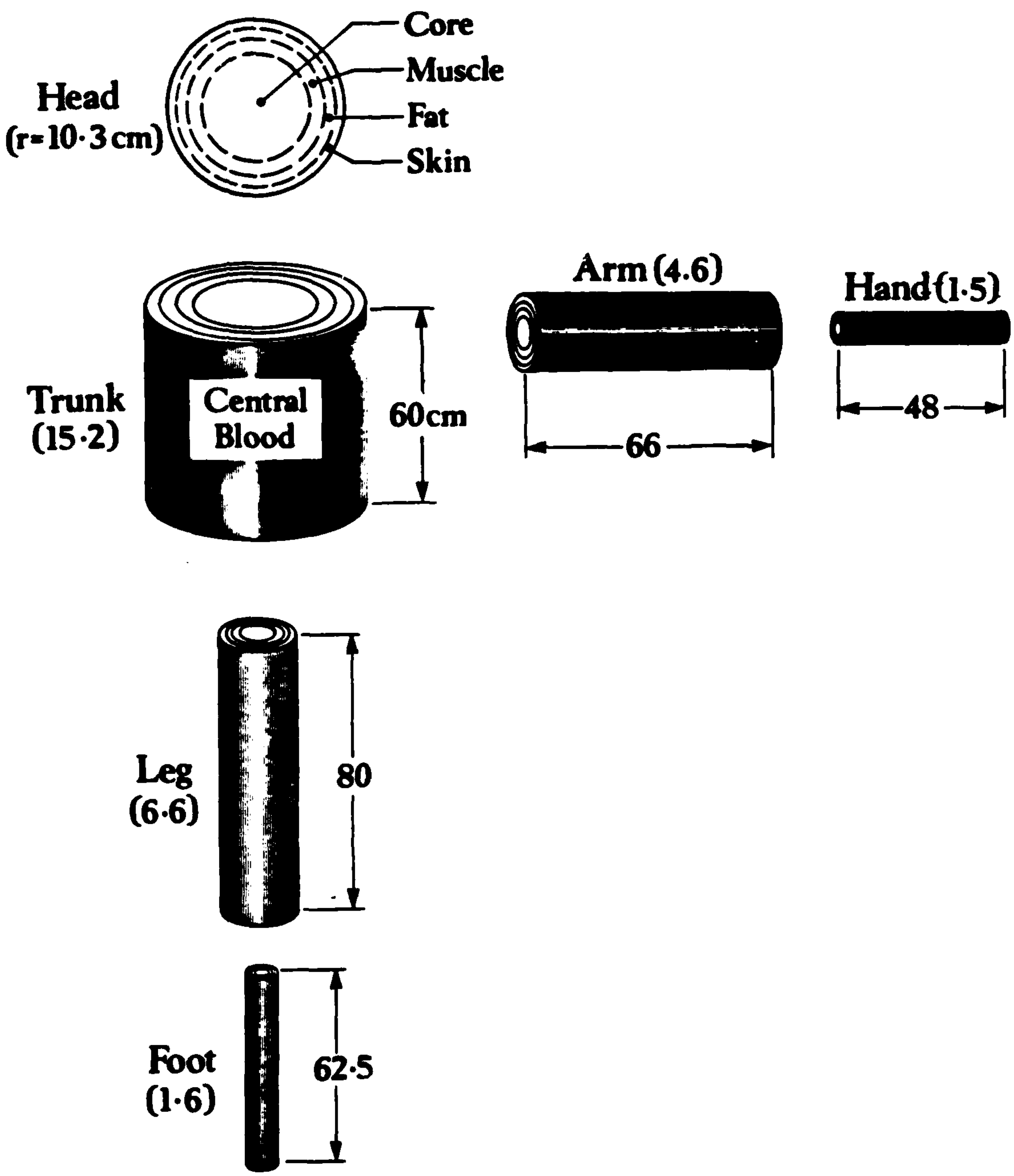
Fig. 3. Measured (●) $\pm$ SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the lean subject group (n=7) immersed in 20°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (20).

Fig. 4. Measured (●) $\pm$ SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the normal subject group (n=6) immersed in 20°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (20).

Fig. 5. Measured (●) $\pm$ SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted aginst time for the lean subject group (n=7) immersed in 28°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (20).

Fig. 6. Measured (●) $\pm$ SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the normal subject group (n=7) immersed in 28°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (20).

Fig. 7. Predicted mean body temperature ($\bar{T}_b$), rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), metabolic rate (M), and convective heat transfer (C), for the normal subject group immersed in 20°C water.



Head
(r=10·3 cm)
Core
Muscle
Fat
Skin
Trunk
(15·2)
Central
Blood
60cm
Arm (4.6)
66
Hand (1·5)
48
Leg
(6·6)
80
Foot
(1·6)
62·5

Fig 1

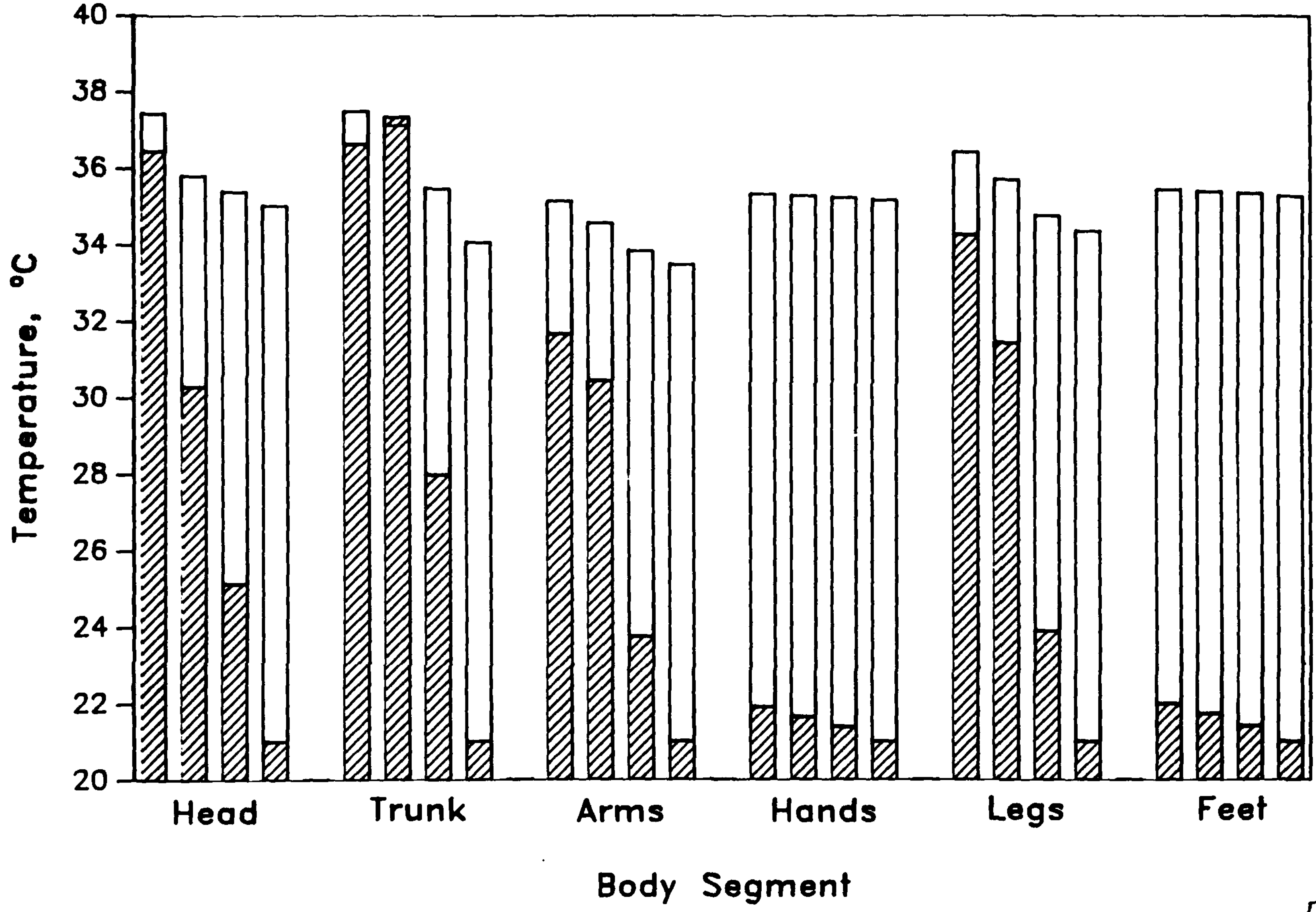
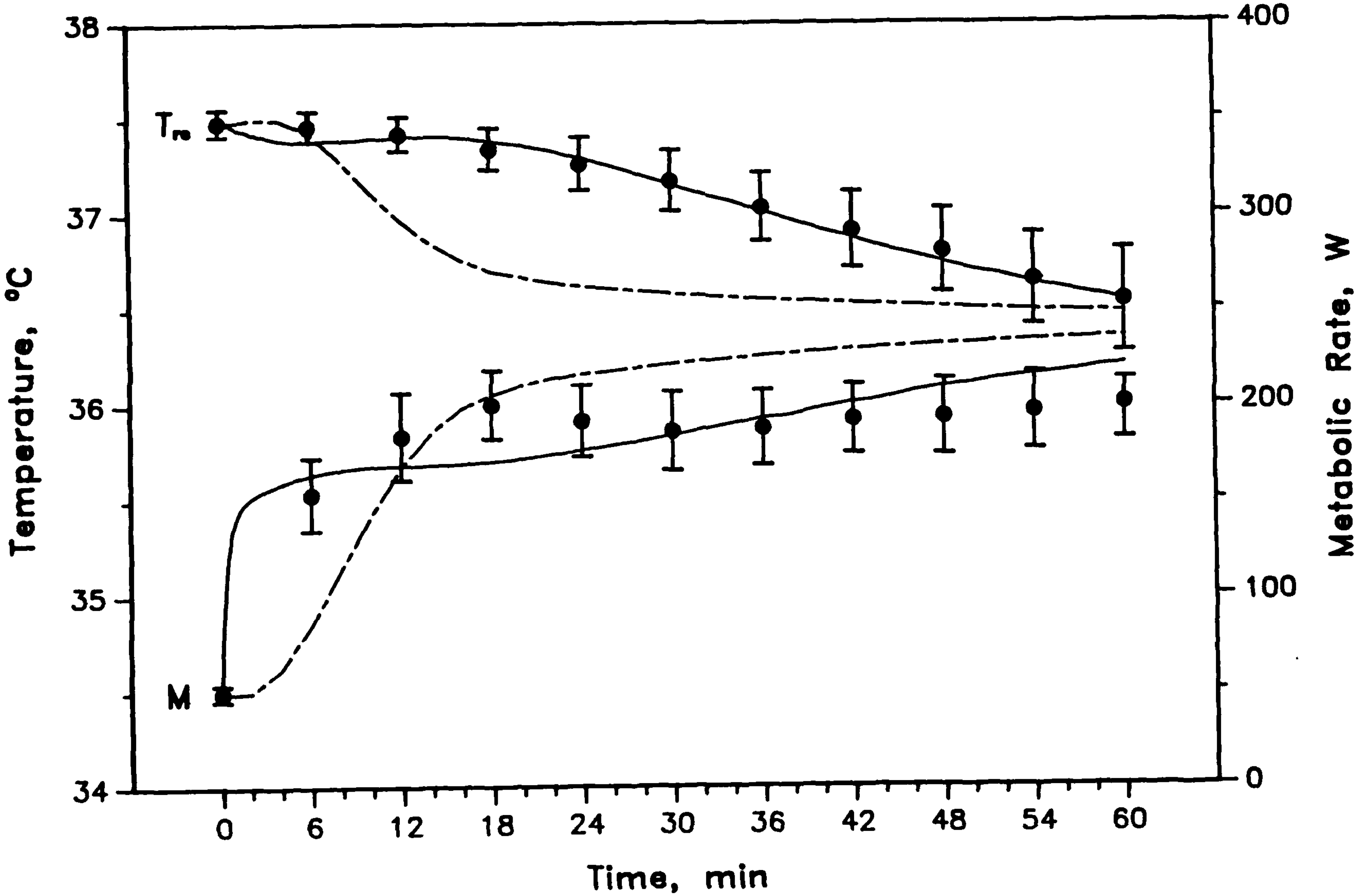
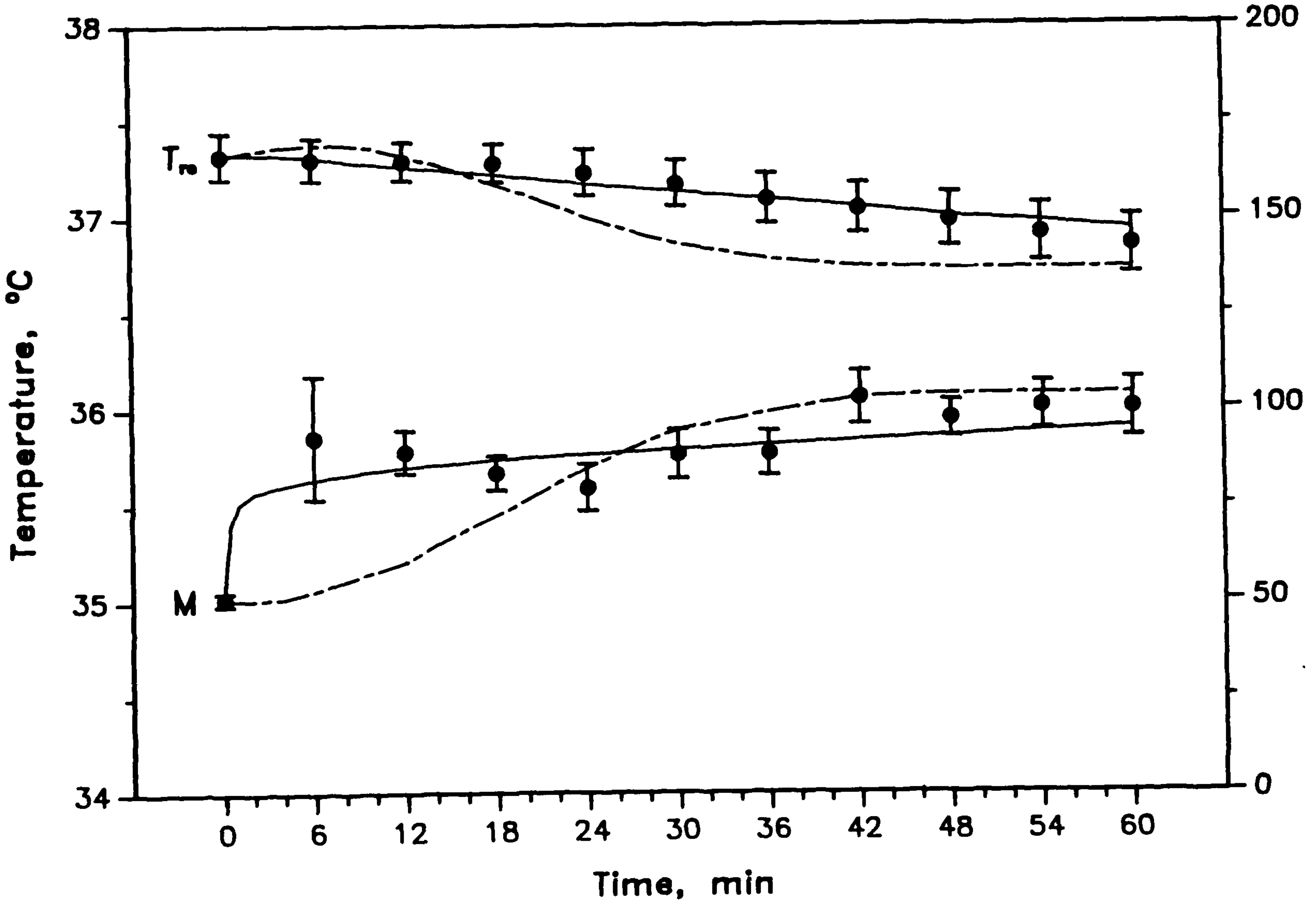

40
38
36
34
32
30
28
26
24
22
20
Temperature, °C
Head
Trunk
Arms
Hands
Legs
Feet
Body Segment

Fig 2



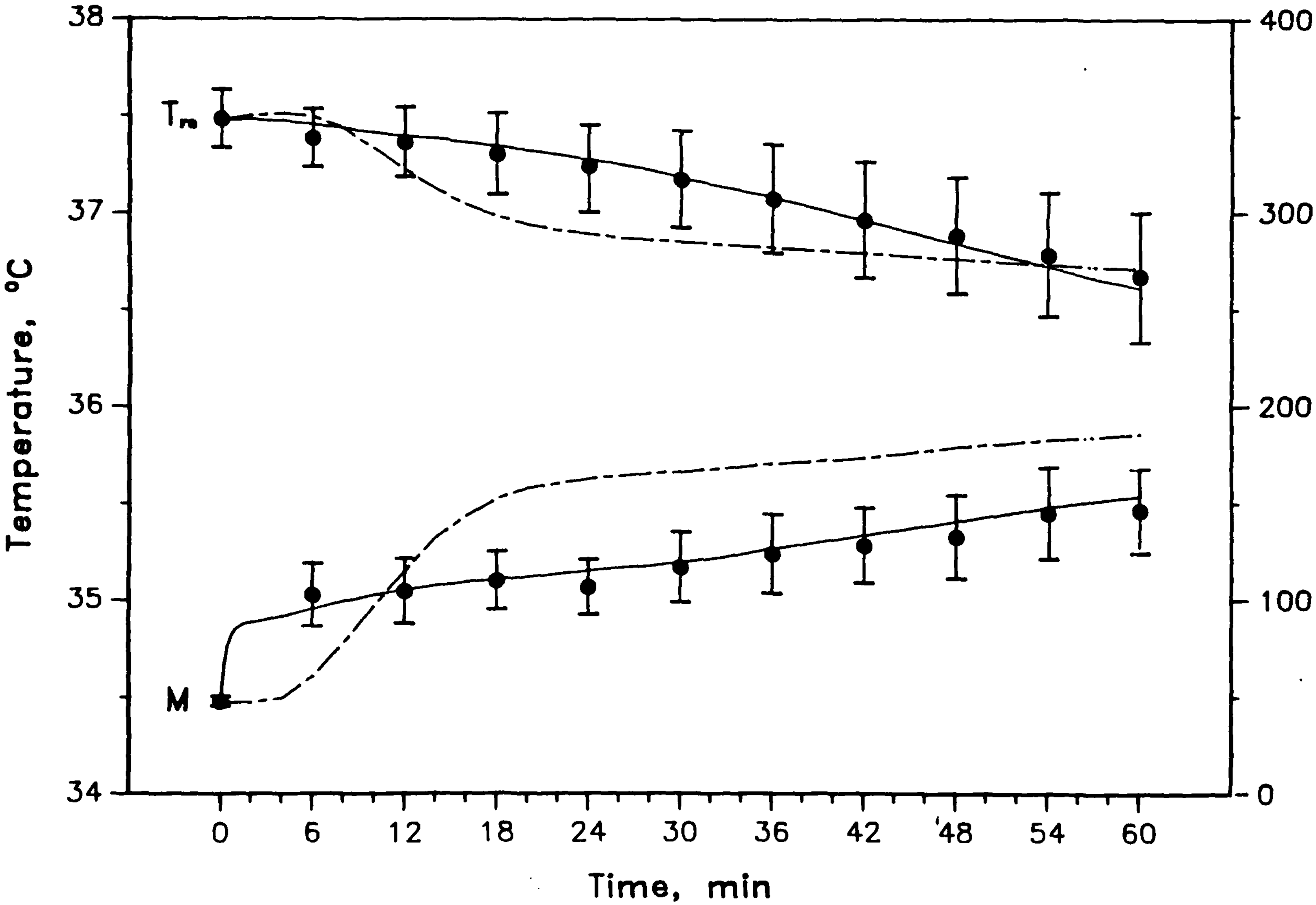
Temperature, °C
38
37
36
35
34
Metabolic Rate, W
400
300
200
100
0
Tre
M
0
6
12
18
24
30
36
42
48
54
60
Time, min

Fig 3



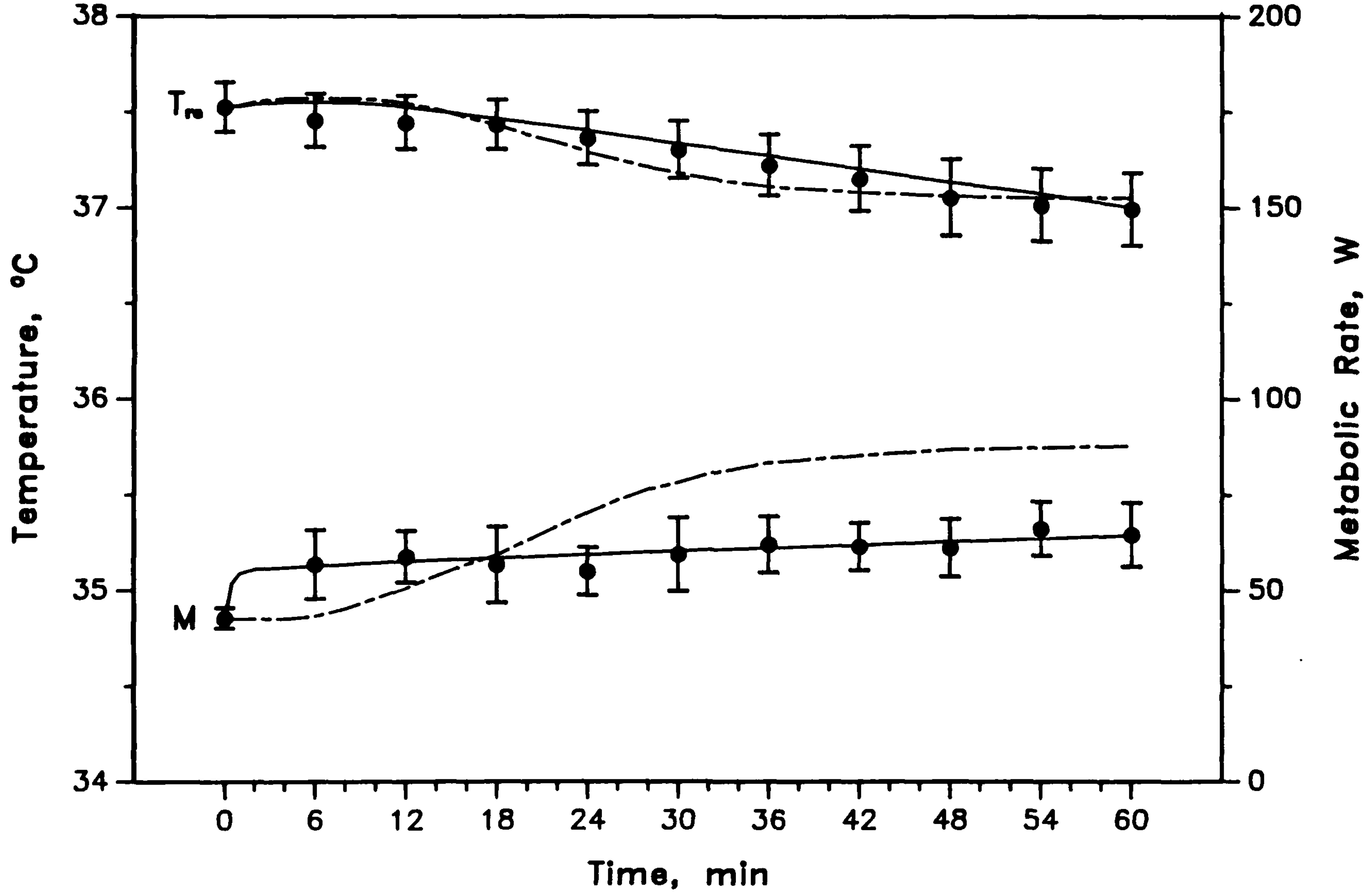
Temperature, °C
38
37
36
35
34
Metabolic Rate, W
200
150
100
50
0
Time, min
0
6
12
18
24
30
36
42
48
54
60
T_{re}
M

Fig 4



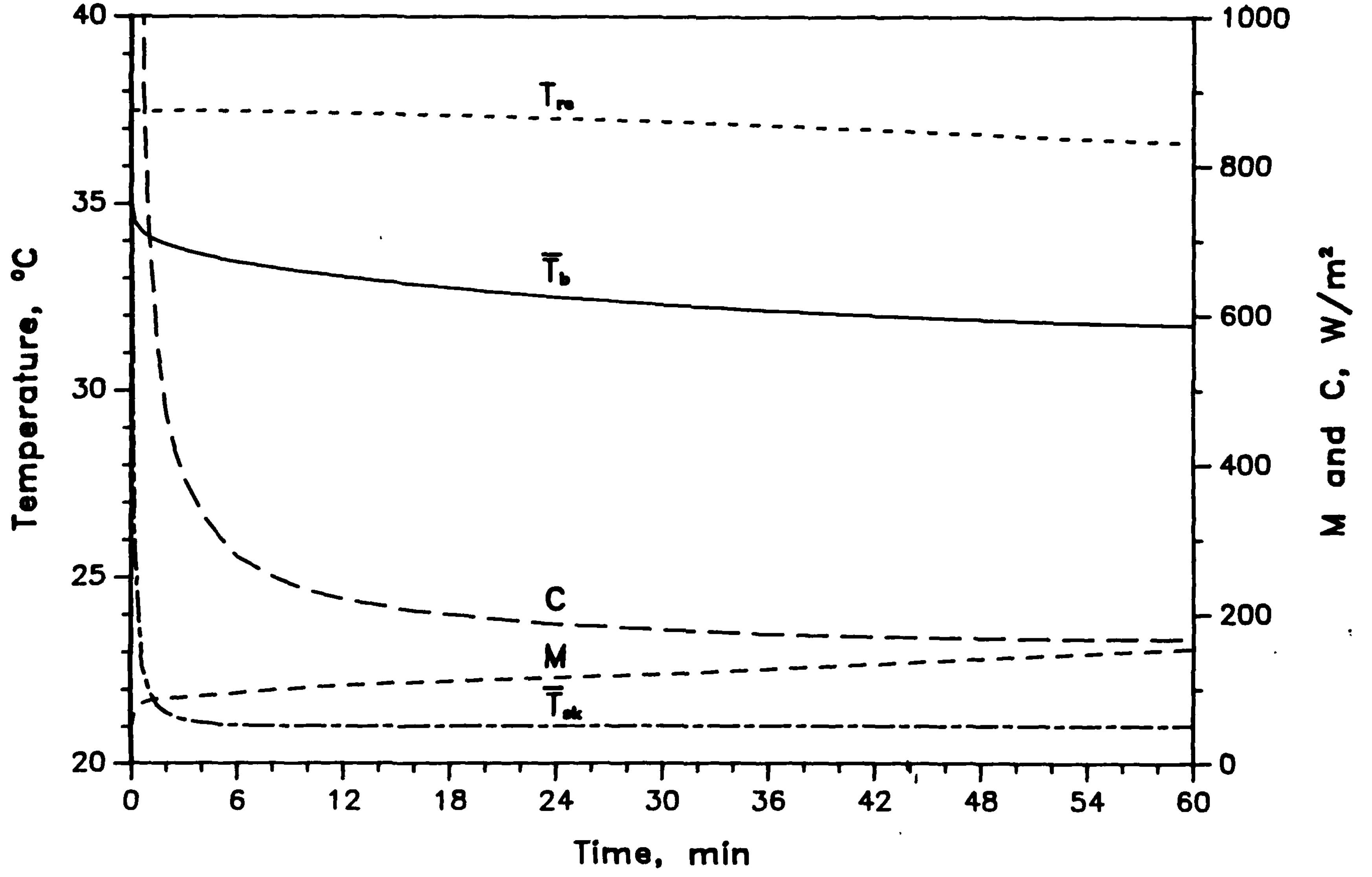
Temperature, °C
Metabolic Rate, W
Time, min
Tre
M
38
37
36
35
34
400
300
200
100
0
0
6
12
18
24
30
36
42
48
54
60

Fig 5



T_{re}
M
38
37
36
35
34
Temperature, °C
200
150
100
50
0
Metabolic Rate, W
0
6
12
18
24
30
36
42
48
54
60
Time, min

Fig 6



40
35
30
25
20
Temperature, °C
0
6
12
18
24
30
36
42
48
54
60
Time, min
1000
800
600
400
200
0
M and C, W/m²
T_{re}
$\overline{T}_b$
C
M
$\overline{T}_{sk}$

Fig 7

END
DTIC
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